Connections Program:
Development of a Hybrid Electric
Powertrain for the Formula SAE Racecar

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BACHELOR OF APPLIED SCIENCE

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Abstract
The purpose of the Formula SAE Collegiate Design Competition is to design, build, and race an open wheel style racecar in order to compete in a combination of static and dynamic events. The current specification racecar utilizes an internal combustion engine from a Honda motorcycle. With the support of Hymotion Canada, this Thesis attempted to direct powertrain development to follow current trends in the automotive industry by developing and testing a prototype parallel hybrid electric/internal combustion engine (ICE) powertrain. The conventional ICE will be adapted to allow the addition of a Brushless DC motor, which will run in parallel to the normal combustion cycle. The creation of a hybrid system should produce more engine torque, thereby increasing the overall performance of the vehicle. With the successful demonstration of the Hybrid System prototype on a mock-up Engine, full testing was conducted on an Engine Dynamometer. After conducting full load testing it was determined that the initial prototype configuration had insufficient power to create any noticeable increase in torque and would require further development to produce any appreciable improvement. Suggestions to improve the hybrid system performance include higher density stator design, the use of a fully adjustable Brushless DC Motor Controller, and running on a higher power circuit.
Acknowledgements

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Akos Toth: For giving me the opportunity to conduct my thesis with Hymotion Canada and offering me the use of their facilities and equipment. Also for sharing his extensive technical aptitude and initiating this project in the first place.

Ontario Centres of Excellence: For providing financial support so that my thesis project could be completed.

Jack Conte: For donating the use of his Engine Dynamometer Test Cell so that I could safely conduct my system testing.

Neal Persaud: For sharing the responsibility of developing and operating the Engine Dynamometer.

Nader: For helping me with the design of PCBs.

University of Toronto Formula SAE Team: For accepting this project as the future of racing.
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1. Introduction

The overall purpose of this thesis is to implement a hybrid electric system into a Formula SAE racecar, which is currently running a conventional internal combustion engine. Once a working prototype has been completed the performance of the system will be measured on an engine dynamometer. When the operational capability of the hybrid system has been determined, considerations for improving the performance and methods of implementation into the racecar will be made. Hymotion Canada is interested in the method of implementation and the performance capabilities of this hybrid system and is providing technical support and access to essential components of the system.

1.1 Formula SAE

1.1.1 Description of the Formula SAE Competition

The Formula SAE (FSAE) Collegiate Design Competition is an annual competition held by the Society of Automotive Engineers (SAE), which asks university students to design, build, and race an open wheel style racecar. Rules for the competition are compiled by SAE and dictate the overall style, performance limitations, and safety requirements of every FSAE racecar. The FSAE competition is divided into two main categories: Static and Dynamic events. Static events include Design, Cost, and Manufacturing presentations. The Dynamic events include Skidpad, Acceleration, Autocross, and Endurance.

1.1.2 Description of the University of Toronto FSAE Powertrain System

There are three main components to a FSAE racecar: chassis, suspension, and powertrain. The chassis holds all the parts of the vehicle together including the driver, suspension, body, and
powertrain systems. The suspension system transmits the forces from the road into the chassis and characterizes the handling capabilities of the vehicle. The powertrain system consists of an Internal Combustion Engine (ICE) and mechanical drivetrain, which includes differential, final drive sprocket, driveline, and drive shafts.

The powertrain engine is restricted by the rules to an overall capacity of 0.61 litres and must breathe through a 20mm restrictor [1]. The current ICE utilized by the University of Toronto FSAE team is a Honda CBR600 F4i motorcycle engine with a capacity of 0.599 litres. The rules allow for modifications to the engine system to improve operating performance. The main goal of the engine team is to increase overall engine output torque over a wide range of engine operating speeds in order to improve drivability and acceleration. To this end, the team has designed and fabricated custom intake and exhaust systems and optimized the internal structure of the engine.

In order to further expand the development of the motorcycle engine platform, this thesis proposes the conversion of the current ICE platform to a parallel hybrid electric system.

1.2 Hymotion Canada

Hymotion Canada is a company that specializes in hybrid vehicle technology. Their main product is the plug-in-hybrid electric vehicle (PHEV) system, which is a modification of currently existing hybrid vehicles. Current hybrid vehicles consist of a regular ICE running in parallel with an electric motor/generator. The advantages of this system allow for greater fuel economy and reduced emissions while still providing the same amount of power compared to a similarly sized conventional vehicle. The Hymotion PHEV system adds an additional high
capacity lithium-ion based battery pack and allows the vehicle to be plugged into a regular electrical outlet for recharge. Because of the extra electrical storage capacity the hybrid vehicle can run for greater distances without requiring the operation of the ICE or having to refill the car with gasoline. This results in an overall improvement in fuel consumption and reduction in harmful emissions.

Hymotion Canada provided their expertise in the design and testing of hybrid systems for this thesis. They provided the power and control systems for the electric motor as well as the expertise required to run the hybrid powertrain system. Assistance was also provided in the design and outsourcing of Printed Circuit Boards required for the conversion. Hymotion is mainly interested in the transformation of the ICE into a hybrid architecture and the overall performance capabilities.

1.3 Thesis Purpose and Objectives

The purpose of this Thesis Project is to determine if the current ICE platform used in the Formula SAE Racecar can be converted to a Hybrid Electric Configuration. If the hybrid conversion is successful, an engine dynamometer will be used to determine the effectiveness of the system, and upon completion, suggestions as to how to better improve performance and actually implement the system into the racecar can be made.

Objectives accomplished to complete the thesis project are listed below followed by a brief description. These objectives will also form the basis of this Thesis report.

1. Background Theory Research, Study of Existing Brushless DC Motors
A literature review of Hybrid Vehicle technology and the operation of brushless DC Motors was conducted. An existing brushless DC motor was dismantled to better understand the motor operation.

2. Engine Dynamometer Completion

An engine dynamometer, which would be the main instrument in measuring the performance of the Hybrid System, as well as testing other ICE components, was completed.

3. Implementation of a Brushless DC Motor into the Honda CBR600 F4i motorcycle engine

The Brushless DC motor was successfully installed into the ICE. The hybrid prototype successfully ran.

4. Engine Dynamometer Testing

The Hybrid System was installed onto the Engine Dynamometer. The Hybrid System failed to generate any noticeable increase in engine power. The maximum speed of the motor was also determined.

5. Suggested Improvements

From the results of the Dynamometer testing, it was determined that more effort will be required to improve the performance of the hybrid system to achieve the desired increase in engine torque.
2. Research Review and Its Application to System Design

2.1 Hybrid Electric Vehicles
Typical motor vehicles that utilize ICEs allow for excellent performance and range for a given fuel but at the cost of poor efficiency and the production of harmful emissions. Fully electric vehicles running electric motors and utilizing batteries as their main power source are representative of a highly energy efficient and zero-emissions vehicle but cannot match the ICE for performance and operating range. But, if these two systems are combined into a hybrid system the advantages of both systems can be realized while minimizing the disadvantages. It is the goal of this thesis to transform the current ICE platform for the FSAE racecar into a hybrid electric system utilizing a Brushless DC Motor (BLDC) as the electric motor-generator.

2.1.1 Hybrid Electric Architectures [2]
There exist two different hybrid electric architectures: parallel and series. The series architecture (Fig. 1) describes a system where the ICE has no direct mechanical connection to the transmission. The sole purpose of the ICE is to power an electric generator. This electric generator charges a large number of batteries, which act as the primary power sources for the vehicle. Electric power from the batteries is used to drive electric motors either in the wheels or connected to a transmission, which drives the wheels. If the batteries are drained to a level below some preset threshold level, the ICE will turn on to recharge the batteries during operation.

The parallel hybrid architecture (Fig. 2) is what most closely describes the system being developed for the FSAE racecar. An electric motor-generator (EMG) is directly linked to the output of the motor, or the transmission of the vehicle. Both the transmission and the EMG are
linked to the wheels of the vehicle. The parallel hybrid architecture allows for greater flexibility in operation, where the EMG serves the dual purpose of both driving the wheels and charging the battery. Having the ICE and EMG both attached to the drive wheels also allows greater flexibility in selecting an appropriately sized ICE or EMG to reach a pre-specified power output. In addition, converting an existing ICE to a parallel hybrid architecture may actually increase the output power of the whole system. The designer can then choose to improve the overall power or fuel economy of the powertrain system.

The parallel hybrid architecture would allow for several different modes of operation.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICE Only</td>
<td>The ICE is directly driving the wheels with no assistance from the EMG.</td>
</tr>
<tr>
<td>Electric Motor Only</td>
<td>The electric motor is directly driving the wheels with no assistance from the ICE. For the FSAE hybrid, this would describe the operation of a starter.</td>
</tr>
<tr>
<td>Electric Motor Assist</td>
<td>Both the ICE and electric motor run at the same time with the electric motor effectively increasing the power and running speed experienced by the wheels of the vehicle, in addition to what the ICE can produce on its own.</td>
</tr>
<tr>
<td>Electrical Regeneration</td>
<td>While the ICE is in operation the EMG can be switched to generate electricity to recharge the batteries.</td>
</tr>
</tbody>
</table>

Table 1 – Parallel Hybrid Architecture Modes of Operation
The EMG in the parallel hybrid architecture can take several other positions in the overall vehicle and ICE architecture. For instance, the EMG can be placed inside the engine directly attached to the output of the ICE for direct action and regeneration. The EMGs can exist outside of the ICE system and can take the form of direct drive motors attached to the wheels of the vehicle. A current example of the parallel hybrid architecture is the Honda Civic Hybrid, which utilizes one EMG attached to the ICE, which is linked to the transmission. [7]

The prototype FSAE parallel hybrid system will utilize an EMG attached directly to the crankshaft of the engine. It has been determined that this is the easiest way to attach an electric motor to the existing ICE system. The hybrid system will be able to perform all the modes of operation as described above. Because of the different goals of this hybrid system, as will be described in the next section, a large capacity electrical power storage system will not be required.

### 2.2 Permanent Magnet DC Electric Motors

#### 2.2.1 Theory of Operation [4]

Brushed and Brushless (BLDC) DC electric motors are comprised of common parts which are described below:

| **Stator** | The stationary part of the motor. |
| **Rotor** | The rotating part of the motor. In a BLDC motor this is the permanent magnet generating the magnetic flux required for generating torque. |
| **Field System** | The part of the motor that generates the magnetic flux required for generating torque. In a BLDC motor, the field system is usually a |
permanent magnet contained in the Rotor.

<table>
<thead>
<tr>
<th>Armature</th>
<th>The part of the motor that transmits electric current which interacts with the magnetic flux generated by the field system. In a BLDC motor, this is usually contained in the Stator as a series of wound coils.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commutator</td>
<td>The structure that allows the sequential distribution of current to the armature.</td>
</tr>
</tbody>
</table>

Table 2 – Common parts of DC Electric Motors

The fundamental laws governing the operation of DC electric motors are Faraday’s and Ampere’s Law which describe the interactions of current carrying conductors and a magnetic flux. When an electric current is applied to the armature of a DC electric motor, the interaction with the magnetic flux generated by the permanent magnet creates a force on the rotor. In order for the motor to rotate, isolated sets of coils in the armature must experience a current in a sequential fashion. Sequentially applying current to each coil in the armature is what allows the rotation of the electric motor and is called commutation.
The difference between a brushed and brushless DC motor are their methods of commutation. The brushed DC motor utilizes a set of brushes, which come into contact with a commutator. The commutator is divided into segments and each segment is individually connected to the different sets of coils. As the brush comes into contact with a segment, current flows from the brush, into the commutator segment attached to a coil, and back out the opposing brush.

A brushless DC motor utilizes a set of magnetic proximity or optical sensors to determine the location of the magnetic poles of the rotor. From this information, a power electronics board can determine which coils require current and sends the current.

Both of these motor types offer the advantages of being controllable over a wide range of speeds, an allowance for rapid acceleration and deceleration, and ease of speed control. The main disadvantage of a brushed DC motor is the commutation system, which requires regular maintenance due to brush wear. Because BLDC motors utilize a non-contact method of
commutation, they do not require regular maintenance. This comes at the cost of the sophisticated power electronics and sensors. [5] pg. 920

A DC electric motor can also be utilized as a generator. If the output of the motor is disconnected from the load and is instead driven by an external force, the same electromotive force is generated and a current flows through the armature. If the speed of the motor driven by the external load is greater than a characteristic no-load rotational speed, a voltage above the voltage supply is generated. This is what allows the hybrid system to operate as both a motor and generator.

2.2.2 Study of an Existing BLDC Motor

In order to study the operation of a BLDC motor, Hymotion provided an ETEK BLDC Motor and Controller from Briggs and Stratton. The main goals of studying this motor were to determine how the commutation was accomplished and how the motor interacted with the supplied controller.

Determining how the commutation was accomplished was required in order to adapt the proposed BLDC motor for this project. A sensor board utilizing 3 hall effect sensors is used in
the Briggs and Stratton BLDC motor to detect the position of the rotor. The rotor is a large conical permanent magnet with alternating magnetic poles. The hall effect sensors detect magnetic fields and switch based upon the polarity of the field it is detecting. The controller uses the sensor information to determine the relative location of the rotor and its orientation of magnetic poles. Based upon this information, the controller calculates which coils must be energized in order for the motor to smoothly operate.

### 2.2.3 Utilization of a BLDC Motor

It has been decided, with the help of Hymotion Canada, that the EMG used for the FSAE hybrid system will be a brushless DC motor. Due to a non-disclosure agreement with Hymotion Canada, the actual specifications and the method of implementation of the motor utilized are purely confidential.

### 2.3 Design Goals of an FSAE Hybrid System

#### 2.3.1 Hybrid System Integration in Passenger Vehicles

The main disadvantages of a typical ICE are the highly inefficient consumption of fossil fuels and the production of harmful emissions. Due to environmental and energy concerns, governments have regulated that future automobiles have excellent fuel economy and reduced emissions. This is combined with the contradictory consumer demand for performance characteristics equal to that of existing automobiles that do not have to meet these regulations. The parallel hybrid architecture was introduced as the lowest cost near-term solution ([2] pg. 24) to meet this demand.
One of the greatest advantages of the hybrid architecture is its ability to increase the performance of an existing ICE. A pure electric vehicle running only on batteries cannot nearly match the performance and range of a modern ICE powered vehicle, but a hybrid architecture will actually increase both the performance and range of the vehicle. Therefore, when designing a hybrid system for energy efficient applications, often the ICE is undersized for that application, with EMGs used to augment the system back to the original application’s requirements. With a greater dependence on the EMGs to propel the vehicle, the overall reliance on the ICE is reduced, requiring the ICE to run less often and, when operating, to remain in its most efficient operating speed/range.

2.3.2 Hybrid System Integration into the FSAE Racecar

Parallel Hybrid systems can improve many different driveline events including vehicle launch and acceleration. The response of EMGs to an increased demand for torque is much faster than an ICE and this is what motivates the creation of the FSAE hybrid system. Therefore, the main purpose of the FSAE hybrid system will not be to reduce emissions or to allow a downsizing of the ICE, but to increase the overall acceleration of the racecar.

A typical FSAE competition racetrack is based on Autocross style racing. An Autocross track is usually a very tight course marked by traffic cones. The width of the track is usually very narrow which attempts to encourage drivers to choose a pre-determined path around the track without deviating from the path laid down by the cones. As well, the nature of Autocross suits racecars capable of high rates of acceleration and excellent handling capability, thereby discouraging overall power and top speed. Therefore, the optimal characteristics of an Autocross specific racecar are high rates of acceleration, a broad usable range of engine output torque,
excellent throttle response, and excellent handling capabilities. A hybrid system can improve both the rate of acceleration, engine torque, and throttle response.

Typically a large capacity electrical power storage system is required for a hybrid vehicle in order to allow the continual operation of the EMGs. The intention of the FSAE hybrid system is to supplement only the acceleration of the racecar for short periods of time when the vehicle requires the greatest rate of acceleration. Therefore, if the hybrid system is only being used to boost the engine’s torque for short periods of time, the power storage system does not need to have the high capacity of a commercial hybrid system. When torque boost is not required, then the hybrid system can switch to a regenerative mode to recharge the electrical storage system.
3. Electric Motor Apparatus and Prototype

3.1 BLDC Controller

As described in 2.2.1, BLDC motors require a complex electronic controller system in order to perform the commutation required to drive the motor. In order to facilitate the production of the hybrid prototype, Hymotion has provided a BLDC controller used in another BLDC motor, which can be adapted for use in this project. The BLDC controller is from the ETEK BLDC motor line from Briggs and Stratton. The capabilities of this controller are very limited and would only be suitable for the prototype and initial testing stages.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power Supply</strong></td>
<td>36 Volts</td>
</tr>
<tr>
<td><strong>Position Feedback</strong></td>
<td>3 Magnetic Hall Effect Sensors</td>
</tr>
<tr>
<td><strong>Speed Control</strong></td>
<td>Not Adjustable</td>
</tr>
</tbody>
</table>

Table 3 – Specifications of ETEK BLDC Controller

The controller runs on a 36V power supply and requires feedback from three hall effect sensors, which detect the position of the bipolar permanent magnet rotor. The speed, and therefore the electric power driving the motor, is not adjustable.

The required 36 Volt power supply required the use of three 12 Volt batteries, linked in series, to power the Controller. For the prototype stage this would be acceptable, but if implemented onto the racecar would definitely be a deterrent in future development. Currently the FSAE Racecar runs on a 12V system and runs a very light weight lead acid battery. To implement a 36 Volt system would require the development of a complex power management system, in addition to a heavy weight penalty. Therefore, further development would entail either powering the system...
utilizing the existing 12 Volt circuit or changing to a light weight power supply such as a lithium-ion or nickel metal hydride battery cell running at higher voltage.

The restriction of not being allowed to control the speed of the motor limits the range of testing allowable on the prototype hybrid system. Most BLDC controllers would allow for a user controllable input controlling the amount of power supplied to the motor, thereby controlling the motor speed and output torque. The configuration of the ETEK controller supplied has been factory specified to only run at one speed. In order to move beyond the initial prototype stage a new controller will need to be implemented which will allow the control of output power to the BLDC motor. Overall, the current ETEK controller is sufficient to perform the initial prototype testing.

3.2 Hall Effect Sensor Board Design
In order to properly adapt the BLDC motor into the ICE, the method of commutation had to be determined. The motor to be implemented required a custom commutation solution. As described in section 2.2.1, BLDC motors require outside feedback in order to determine which coils in the stator to energize. Common methods of accomplishing this include the use of an optical detector or encoder or magnetic hall effect proximity sensors. Due to size constraints, hall effect sensors were utilized. Hall effect sensors usually take the from of electronic switches which close when placed in a magnetic field, and open when placed in the opposite magnetic field.

In order to detect both the position and direction of rotation of the motor, three sensors must be used. Depending on the number of magnetic pole alterations on the rotor, the spacing between
the sensors can be determined. The rotor being used has 6 north and 6 south poles, and therefore 12 pole alterations (fig. 7). The magnetic poles are evenly distributed around the rotor, with each pole occupying an angular rotation of 30°. For this configuration, in order to both detect the position and rotational direction of the rotor, two sensors must be closed while in proximity to one pole while the third is open while in proximity to the adjacent opposite pole. To achieve this effect, the sensors must be placed at an angular position of 20° from each other.

![Figure 7 – Orientation of magnetic poles in the rotor and location of hall effect sensors](image)

The next step was to choose sensors that would meet the demands of the application including operational, size, electrical, and environmental constraints. A Bipolar Hall Switch from Melexis [6] was selected which met all the requirements demanded by this application. The requirements and the specifications of the sensor are detailed below.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Sensor Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum speed to detect</td>
<td>2.4 kHz – 10 kHz</td>
</tr>
<tr>
<td>Size</td>
<td>Smallest dimension, 15mm – Package size 2.75mm X 2.9mm</td>
</tr>
<tr>
<td>Electrical Supply</td>
<td>12 Volts DC – 3 – 24 Volts DC</td>
</tr>
<tr>
<td>Environmental Constraints</td>
<td>Submersed in oil at maximum 120° C – Max operating temperature 150° C</td>
</tr>
</tbody>
</table>

Table 4 – Hall Effect Sensor Requirements and Melexis Sensor Specifications
The final step was to design a custom printed circuit board (PCB) that would fit the space constraints, accept the hall effect sensors, and survive the environmental conditions during operation. The board was designed utilizing Protel software and extensive consultation with Hymotion.

Allowance was made for two mounting holes, which would be attached to a modified bracket inside the motor. These holes would also act as grounding points linked to the ground plane on the bottom layer of the board in order to reduce electrical noise contamination.

Once installed, the board had to be protected from environmental conditions inside the motor including direct contact with high temperature oil, high frequency vibration, and the possibility of contact with foreign materials, which could damage the PCB, sensors, or lead wires. The lead wires were protected by a sheath of heat shrink in order to prevent external damage to the wiring.
The actual PCB and sensors were coated in a layer of protective silicon based potting acting as both a protective and non-conductive layer.

3.3 BLDC Motor Prototype Installation
Due to the uncertainty involved with testing a completely unfamiliar system and the high cost of the ICE, a prototype testing platform had to be used. Fortunately, an ICE, which was damaged beyond repair, but still contained the required components to run the prototype was available. This ICE included the engine block, crankshaft, and pistons, all of which are driven by the BLDC motor. The entire valve train and engine head were removed from this ICE, which would dramatically change the operation of the motor. The valve train is what allows the ICE to compress air for combustion, and without these components installed on the prototype ICE, actual loading conditions seen during actual operation would not be replicated. Therefore, the prototype hybrid system would be completely unloaded and would only accomplish the task of identifying whether or not the prototype would operate.

![Prototype motor, 32V power supply, and BLDC Controller as installed](image)

Figure 10 – Prototype motor, 32V power supply, and BLDC Controller as installed
With the BLDC motor controller prepared and the custom hall effect board complete, all system components were ready for the prototype to be run for the first time. After several trial runs the prototype was able to run quite effectively. Crude measurement of the engine rotational speed using a handheld rotational tachometer approximated the maximum speed to be 2500 RPM. This rotational speed actually closely represented the No-Load speed as found during dynamometer testing. Because this speed was reached, it can be assumed that the prototype ICE did not place any load on the BLDC motor. The system was also subjected to short endurance runs for a duration of three minutes, all of which were completed without incident. At this point the prototype hybrid system was ready to be installed in a fully functional ICE and load tested on an engine dynamometer.
4. FSAE Hybrid System Prototype Testing

The prototype hybrid system was tested on an engine dynamometer, which is capable of measuring the output torque of the engine. Because the basic architecture of the F4i engine remained the same after the modifications, testing on the engine dynamometer would follow the same procedures as testing a conventional ICE.

4.1 Description of the Engine Dynamometer System

The basic parts of an engine dynamometer are described in the following table:

<table>
<thead>
<tr>
<th>Part</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque Arm</td>
<td>The torque arm is directly attached to the output of the engine and experiences the torque generated at the output. By measuring the strain in the arm, torque measurements can be made.</td>
</tr>
<tr>
<td>Water Brake</td>
<td>In order to take meaningful torque measurements, a load must be applied on the engine. This load allows the speed of the engine to be controlled. Water is used to resist the rotation of the engine.</td>
</tr>
<tr>
<td>Hydraulic Valve</td>
<td>The hydraulic valve restricts the water flow to the water brake. As flow increases, the load on the engine increases. This valve is electronically controlled.</td>
</tr>
<tr>
<td>Data Acquisition</td>
<td>The data acquisition system collects all the information about the engine operating conditions during a test. This includes output torque, engine speed, throttle position, coolant temperature, intake air temperature, and exhaust gas air/fuel ratio. After the data has been collected it can be plotted for later analysis.</td>
</tr>
<tr>
<td>Control System</td>
<td>The control system takes as its input the engine speed. The controlled variable is the hydraulic valve. The desired input is an engine speed the dynamometer operator wishes to take measurements at. The controller will open or close the hydraulic valve until the engine reaches the desired engine speed.</td>
</tr>
</tbody>
</table>

Table 5 – Major parts of the Engine Dynamometer
4.2 Dynamometer Testing Objectives and Plan

The purpose of testing the hybrid system on the engine dynamometer was to determine the functionality and characterize the performance of the system, which would help in the implementation stage of development. It is important to have a baseline so that significant comparisons of performance can be made. The baseline will be the standard ICE without the integrated hybrid system. Therefore, all performance improvements will be compared to the baseline ICE-only system. The following table lists the testing objectives, a description of what test will be performed, and their effect on the implementation stage.
<table>
<thead>
<tr>
<th>Objective # 1</th>
<th>Prototype Shakedown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Description</td>
<td>The purpose of this test will be to determine the mechanical and electrical stability of the hybrid system. Each mode of operation will be tested to determine if the system is functioning properly. Modifications may be required in order to improve system functionality. As well, normal operation of the engine will be tested to ensure that the hybrid system does not disturb the normal ICE-only operation.</td>
</tr>
<tr>
<td>Effect on Implementation</td>
<td>This will be testing the fundamental operation of the hybrid system and will probably be representative of the final EMG implementation into the ICE system.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Objective # 2</th>
<th>Effects of Power Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Description</td>
<td>A baseline engine torque measurement at 5 different engine speeds (between 7000-11000 rpm) will be taken without the operation of the EMG. Subsequent tests will increment the electrical power applied to the EMG. During each of these power steps, torque measurements will be taken at each of the 5 different engine speeds. The baseline will provide the benchmark to compare the effect on torque by different applied power levels to the EMG.</td>
</tr>
<tr>
<td>Effect on Implementation</td>
<td>Using the collected data, a map of different torque boosts can be plotted versus engine speed and applied power. The map will be used to help determine what power must be applied to the EMG for optimal acceleration under different on-track conditions.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Objective # 3</th>
<th>System Life Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Description</td>
<td>This test will determine how long the torque boost can operate until the supply voltage goes below a certain threshold. To simplify measurement, over the previous 5 engine speeds, and a set of 5 different operating voltages (to be determined from objective # 2), the time for the battery to drop below the threshold voltage will be</td>
</tr>
</tbody>
</table>
measured. This threshold voltage (dependent on battery) would be a voltage level that would be detrimental to the continued operation of the normal ICE electronics.

| Effect on Implementation | The results will determine the maximum length of an engine boost before the battery must be recharged. |

**4.3 Dynamometer Test Results**
Upon installation of the hybrid system into the full ICE, including the engine head and valve train, the BLDC motor was activated while the ICE was not operating. These conditions included the full load of compressing or scavenging air from all four cylinders of the ICE as well as the additional load of operating the valve train. Unfortunately, the BLDC motor was not powerful enough to rotate the static motor. Because the BLDC motor was essentially stalled, the motor demanded an extremely high amount of current, in an attempt to turn the motor, and resulted in a very high voltage drop (from 36 V to 24V) and a large temperature rise in the connecting wires. Due to the dangers of starting an electrical fire, the system was deactivated. Having essentially failed the static test, it was decided to proceed with testing the hybrid prototype with the ICE operating in an attempt to quantify the power output of the BLDC motor.

Because the BLDC motor speed could not be adjusted it was decided to test only at lower ICE speeds so the rotation velocity did not exceed the no-load speed and potentially damage the batteries. After running the ICE at speeds from 1000-3000 RPM, with the BLDC motor turned both on and off, no discernable effects on torque output were observed. From 2800 RPM and above, battery voltage began to rise from the no-load 36V to upwards of 40V, therefore identifying 2800 RPM as the no-load speed. Any rotational speed beyond 2800 RPM would begin to recharge the batteries.
4.4 Dynamometer Testing Conclusions

After completing the initial tests on the engine dynamometer, the overall effectiveness of the hybrid prototype could be easily determined. The hybrid prototype’s as-tested state was completely underpowered and no observable improvements in torque output were measured. The no-load speed was identified in the range of 2,800-3,000 RPM. In addition to being underpowered, having a very low no-load speed would not be very effective for an FSAE application as the majority of time, engine speeds are in the range of 5,000-11,000 RPM. After removing the BLDC motor from the ICE, the hall effect PCB was fully intact and showed no signs of wear. This was after the ICE had completed several other tests while running at top speed and very high engine temperatures, which would be representative of the harshest internal engine conditions.

These results are not considered a failure, but are actually the first steps towards a fully functional system. With the initial prototype proving to be a complete success, the project can move onto improving overall torque output and progressing beyond the prototype stage. Suggestions for future work will be discussed in the next section.
5. Recommendations to Improve Performance

The main performance issue with the Hybrid System is the lack of torque output from the BLDC motor. The operation of the BLDC motor when implemented into the FSAE ICE was successfully demonstrated, so future efforts can be put towards improving the torque output of the motor.

5.1 BLDC Motor Controller

One of the main limitations of the prototype hybrid system was the BLDC motor controller. As stated in 3.1, the maximum power output of the controller was 36 Volts, which was a hard-programmed power output limit. Simply having a controller that could increase the voltage applied to the motor would dramatically increase the torque output of the BLDC motor. Power output control would allow greater variability in torque output. Quite simply, it would allow gradual variations in output power as opposed to the sudden application of maximum torque. In order to meet this an Advanced Motor Control B100A8 series would be ideal. This controller is capable of delivering power up to 4000W at 80 Volts, which would be more than enough power to see dramatic increases in output torque. This controller would also accept the current hall effect sensor PCB.

Figure 12 – Advanced Motion Control BLDC Motor Controller B100A8 [6]
5.2 Hall Effect Sensor PCB
When the design of the hall effect sensor PCB began, assumptions were made as to how the PCB would be mounted into the motor. Based on this assumed position, the locations of each of the three hall effect sensors were chosen. Unfortunately, the presumed position of the PCB inside the motor was not possible and the mounting was based more upon what could actually be accomplished. Therefore, the intended position of the PCB compared to the actual installed position was not the same, and may have caused errors when communicating with the BLDC controller. One of the main reasons it was not possible to accurately place the PCB inside the motor was due to the difficulty in locating any kind of reference point to take measurements. The actual mounting bracket was in fact already in the motor and was simply modified to accept the PCB.

Therefore, in order to improve both the efficiency of motor operation and to prevent errors in locating the position of the rotor, a reference frame within the mounting space must first be established. From the reference frame, accurate measurements can be taken and proper brackets fabricated which will accurately locate the hall effect sensor PCB relative to the rotor.

5.3 Stator Rewinding
The torque output of the motor is directly proportional to the current applied to the armature/stator of the BLDC motor. Torque and current are related by $K_T$, or the torque constant, which is based upon the length of the windings in the stator. Therefore, to increase output torque, it would be advantageous to wind as much length of conductive wire around the stator. At the same time, increasing the density of the windings will allow an even greater
increase in conductor length. As found in work conducted by Honda on their BLDC motor for hybrid electric vehicles [7] using flat wire coil can allow for a greater density of conductor to be wound into the same space over the previous round conductor. Therefore, rewinding of the stator will increase the torque constant thereby increasing overall output torque.

Figure 13 – Examples of stator winding techniques to increase density of winding [7]
6. Integrating the Hybrid System into the FSAE Racecar

The overall goal after the completion of the Hybrid System Prototype would be to integrate the system onto the FSAE Racecar. Testing on the dynamometer compared to actually running the system on the racecar offers a completely new set of challenges that must be overcome before any confidence in the system is developed and it is run in competition. If this stage is ever reached in the future, the following list outlines some of the goals that must be reached.

- Determine the safety mechanisms required for on-track running. Create events that the EMG is allowed to operate and events that the EMG cannot, which also double as regenerative events. Operating events would be the application of full throttle by the driver. Regenerative events would be during braking or other throttle positions less than 90%. Also define a failsafe system that will only allow the EMG to be operated under driver control.

- Create a package for the power electronics, EMG, controller, and power source that will fit into the current racecar structure. This package would have to occupy as little space as possible and have a minimum weight.

- Design a controller that will determine what state the EMG should operate (Motor/Generator), how to optimize the acceleration of the vehicle, and how to ensure that the power source remains at an optimal state. Feedback into the controller will also need to be determined. Feedback could be battery voltage, vehicle acceleration, wheel speeds, throttle position, and brake pressure.

- From on track testing, determine a control scheme to optimize the Acceleration and Autocross dynamic events.
7. Conclusion

The main objective of this Thesis Project was to determine the effectiveness of running a parallel hybrid electric system with the Honda CBR600 F4i motorcycle engine used for the FSAE Racecar. Initial research was conducted and a BLDC motor was chosen to be implemented into the prototype system. With the help of Hymotion Canada, a BLDC motor controller for the prototype was provided as well as design assistance for a custom hall effect sensor PCB to run the BLDC motor.

The BLDC motor provided by Hymotion was successfully installed into the ICE and all the ancillary parts were connected. Initial unloaded testing took place on a wrecked ICE engine effectively placing no load on the BLDC motor. The prototype proved to be a success, rotating the motor at approximately 2500 RPM.

Conclusions from dynamometer testing were easily made: in its current configuration, the BLDC motor was not powerful enough to create any amount of measurable torque. The no-load speed of the BLDC motor was 2800 RPM. With the performance of the hybrid system effectively characterized, suggestions for future improvements to increase the output torque were made. Future work for implementation on the actual racecar was also outlined.

Although no data was collected from the engine dynamometer testing, the project was still a success in its own right, demonstrating that the ICE used by the FSAE team could effectively be adapted to a parallel hybrid configuration. This thesis will only be the first step in the development of a fully hybrid electric FSAE racecar.
8. References


